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Trajectory Simulations, Qualitative Analyses and Parametric Studies of A Laser-Launched Micro-Satellite Using OTIS (Preprint)

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Abstract. This paper will discuss Air Force Research Laboratory (AFRL) Propulsion Directorate's theoretical and computational results regarding trajectory simulations, qualitative analyses and parametric studies of a 25-cm focal diameter Laser Ramjet (X-25LR) using Optimal Trajectories by Implicit Simulation (OTIS). OTIS has been used to produce an optimized trajectory simulation of a laser ramjet's flight to Low Earth Orbit (LEO). The baseline case that has been simulated is a flight vehicle powered by a 1 MW, 10.6 µm, CO_2, ground-based laser (GBL) with an initial power capture of 82%. The fuel that is used during rocket flight is Delrin® doped with energetic additives to increase the coupling coefficient and thrust by a factor of five. Additionally, a nozzle extension was considered which increased performance by 40%. The flight trajectory was separated into three phases: 1) Air-breathing ramjet flight to a specified altitude of ~30 km and Mach number of ~10; 2) Rocket powered flight into a trajectory with a final Mach number ~27; and 3) Un-powered coasting flight to the final altitude of 185 km. Additional sounding rocket trajectory flights with 10-kilowatt class CO_2 lasers have been assessed for a variety of laser powers. Also to be discussed in this paper are the parametric trade studies of the rocket phase comparing high thrust vs. low thrust and the effects of different-size vehicles.

LASER RAMJET/ROCKET CONSIDERATIONS

Chemically-Augmented Laser Ramjet/Rocket

The laser ramjet/rocket in the context of this study is a small (~25 cm diameter) vehicle that "rides" the beam of a ground-based laser (GBL) to LEO. Within the useable atmosphere (up to ~30 km), the LR acted as an air-breathing ramjet, using it's conical fore-body as an external compression surface before the air passed through the inlets of the annular shroud which acted as a combustion chamber. There the air was subjected to an intense laser pulse which had been reflected and concentrated into the shroud's focus by the parabolic after-body of the LR which acted as a mirror and an external expansion surface. This laser pulse resulted in a detonation wave which expanded along the after-body of the LR producing thrust through pressure effects on the vehicle. During the air-breathing phase, the LR was augmented with solid or liquid chemical fuel to increase the available thrust by a factor of three to five. The geometry and physical specifications of the chemical system were not treated in this report.

Above the atmosphere, the LR operated as a conventional rocket, through conservation of momentum as the laser pulses ablated the propellant, which was Delrin® that could be doped with energetic chemicals to increase the coupling coefficient by a factor of five. The total initial vehicle mass consisted of structural mass, a payload mass that was equal to the structural mass and propellant of a certain mass fraction. After the propellant was expended, the laser was turned off and the vehicle coasted to its final orbital altitude.

Sounding Rockets

A sounding rocket in the context of this study was defined as a vertically-launched laser rocket with specific propellant characteristics that was modeled until propellant burn-out was reached. The propellant mass fraction in all cases was 0.67 with a vehicle structural mass of 210 grams and a propellant mass of 420 grams. The simulation cases were run at four separate laser powers: 10 kW; 30 kW; 50 kW; and 100 kW. The propellant used was Delrin® doped with energetic materials for a coupling coefficient, C_m, of 3,150 N/MW and a specific impulse of 300 seconds

THEORETICAL CONSIDERATIONS

Launches to LEO

Air-Breathing Phase

The first phase of the vehicle's flight was the air-breathing phase from the ground to a proposed altitude of ~30 km and Mach number of ~10 with chemical augmentation. During this phase, the vehicle worked as a ramjet with its conical fore-body compressing the air in front of the air inlets prior to the fuel injection and laser-pulse detonation. Since air was not the only propellant during this phase, the vehicle I_{sp} is finite and the air-detonation coupling coefficient was defined by Equation 1 [1].

$$C_m = 92.18\ R_0^{3/4}\ A_{LR}\ \rho_1^{3/4}/E_l^{3/4}\ \eta_{tot} \qquad (1)$$

In this equation, R_0 is the focal radius of the vehicle, A_{LR} is the effective thrust surface area, E_l is the laser energy per pulse, ρ_1 is the air density within the "combustion chamber" and η_{tot} is a total efficiency factor.

The air-breathing phase of the flight to LEO was chemically augmented with liquid or solid fuel. The efficiency of a typical ramjet is defined by its thrust-specific fuel consumption (TSFC) which is defined as shown in Equation 2, where dm_f is the mass flow rate of the fuel, dm_a is the mass flow rate of air, u_e is the exhaust velocity, u is the vehicle flight velocity, τ is the thrust and f is the fuel-to-air ratio.

$$TSFC = dm_f/\tau = dm_f/(dm_a[(1 + f)u_e - u]) \qquad (2)$$

Typical values of TSFC for ramjets are 0.17 – 0.26 kg/(N-hr) [2]. In the case of the air-breathing phase simulated here, the chemical system enhanced the thrust by a factor of five with the TSFC value staying constant at 0.2, which resulted in an I_{sp} of 1835.6 seconds. Thus, as air-detonation thrust increased, the mass flow of the chemical fuel increased to enhance the total thrust by a factor of five.

Rocket Phase

For the rocket phase of the flight, the maximum coupling coefficient and I_{sp} that can be attained is 3,150 N/MW and 300 seconds. According to Dr. Carl William Larson [3], the effect of the addition of energetic propellants to the Delrin® mixture can be explained as follows.

$$\tfrac{1}{2}\, C_m\, V_e = \alpha\, \beta\, \varphi \leq 1 \tag{3}$$

In Equation 3, α is the efficiency of conversion of gas internal energy to jet kinetic energy, φ is the ratio of the propellant's mass-weighted average velocity squared to its mass-weighted root mean square velocity: $\varphi = \langle v\rangle^2/\langle v^2\rangle$ and β is the efficiency of absorption of laser energy [4]. If there is additional energy coming from chemistry, Equation 4 is the result.

$$(\alpha\, \beta\, \varphi)_{apparent} = \alpha\, \varphi\, (\beta + E_{chem}/E_{laser}) = \tfrac{1}{2}\, C_m\, V_e \tag{4}$$

In Equation 4, E_{chem} is the specific chemical energy of the ablated mass. If the values of α, β and φ (i.e. the efficiency without chemical additives) remain constant and the ratio E_{chem}/E_{laser} increases, the product of C_m V_e increases. However, chemical reactions are known to have a limit to the specific impulse capability of approximately 450 seconds. In the case of the Delrin®, the average specific impulse is 300 seconds, and the chemical additives are solid propellant combinations centered on ammonium nitrate and ammonium perchlorate. One can then assume that the specific impulse will not increase markedly through the addition of the energetic propellants. Also, the magnitude of E_{chem} is much greater than E_{laser}, so there is little chance that specific impulse can be increased simply through heating the propellant to higher temperatures with the laser. The coupling coefficient, though, can be increased to a value of 3,150 N/MW through the proposed factor of five thrust magnification due to the energetic propellants and the 40% increase in performance owing to the addition of a nozzle extension to the vehicle [5].

If energetic materials are not used, the maximum coupling coefficient that can be expected is 450 N/MW, which was determined experimentally for Delrin®. However, a trade-off can be made between the coupling coefficient and specific impulse by adjusting the absorption depth of the propellant and allowing the same amount of laser-pulse energy to be absorbed into a smaller volume of Delrin®, raising the specific energy of the propellant, Q^*, significantly. This will raise the specific impulse and lower the coupling coefficient of the propellant based on the diagram of C_m vs. V_e shown in Figure 1 [4].

In Figure 1, the y-axis is the coupling coefficient of the propellant and the x-axis is the exhaust velocity. The asymptotic lines are lines of constant efficiency of conversion of laser energy to exhaust kinetic energy, $\alpha\, \beta\, \varphi \leq 1.0$, and the lines radiating out from the origin are lines of constant propellant specific energy, Q^*. α is the efficiency of conversion of gas internal energy to jet kinetic energy, φ is the ratio of the propellant's mass-weighted average velocity squared to its mass-weighted root mean square velocity: $\varphi = \langle v\rangle^2/\langle v^2\rangle$ and β is the efficiency of absorption of laser energy [4].

If it is assumed that the conversion efficiency is maintained at its value of 66.2% with a coupling coefficient of 450 N/MW and I_{sp} = 300 seconds, while propellant specific energy increases, it can be seen that the coupling coefficient will be reduced while the specific impulse will increase.

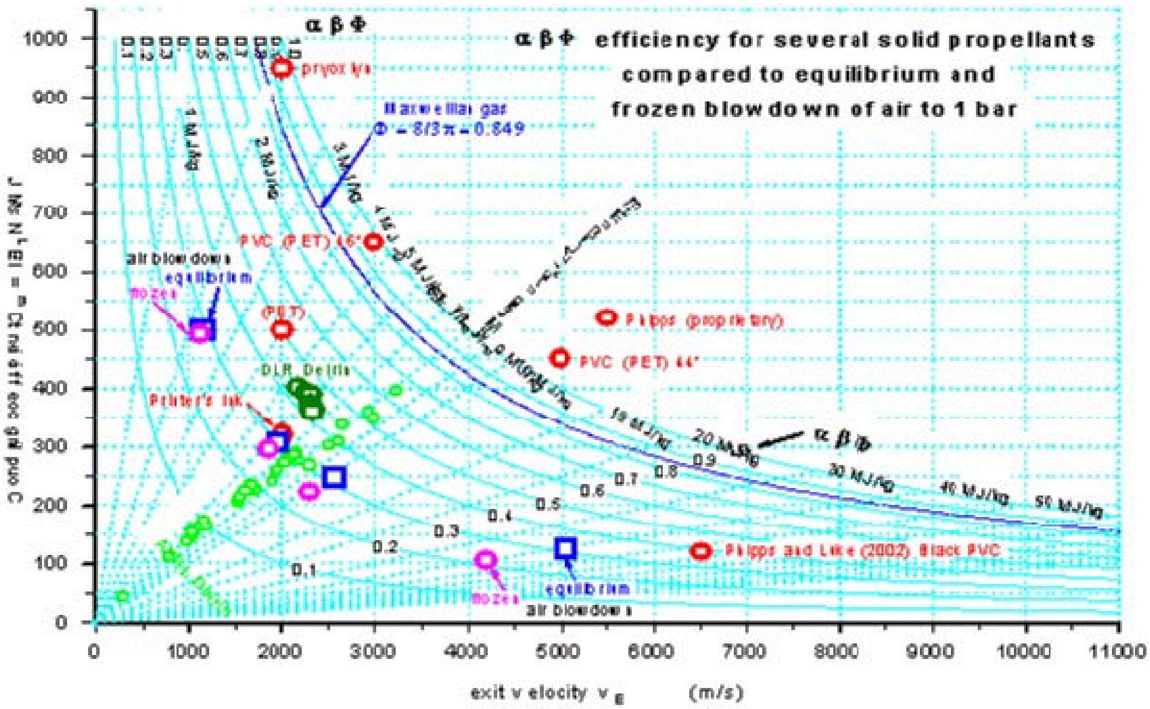

FIGURE 1. Diagram of C_m vs. V_e

RESULTS AND DISCUSSION

Launch to LEO with a 10 MW Laser

The following simulation was conducted under the assumption that, in the future, a 10 MW, 10.6 µm, CO_2 laser could be constructed and used for laser-vehicle launches. Three vehicle phases were simulated starting from a ground-level launch at an altitude of ~10,000 ft: chemically-augmented air-breathing ramjet flight to an altitude ~30 km and a Mach number ~10; a Delrin®-based rocket phase to a Mach number ~27 with a coupling coefficient of 168.77 N/MW and I_{sp} = 800 s; and a coast phase to bring the vehicle to its final altitude of 185 km.

The chemically-augmented air-breathing phase was modeled as having a thrust augmentation of a factor of five with a TSFC = 0.2 (effective I_{sp} = 1835.6 s), the efficiency was 65% and a plasma-based drag reduction scheme was assumed for the air-breathing phase that reduced drag by 45%. The initial laser power captured by the vehicle at ground level was 82%, but atmospheric effects began to have a marked effect on incident laser power at a range of 10 km from the laser.

The initial mass of the vehicle was 6.8 kg (15 lbs.) and propellant mass fractions for each of the stages (air-breathing and rocket) were limited to no greater than 0.5 for a total limit on mass fraction of 0.75 leaving a final mass of 1.7 kg for structure and payload.

The chemically-augmented air-breathing phase of the flight lasted for 24.29 seconds and had a final altitude of 31.51 km (19.6 mi) with a final Mach number of 11.14, the rocket phase lasted for 10.45 seconds (34.74 seconds of total flight) and had a final altitude of 82.28 km (51.1 mi) with a final Mach number of 26.5 and the coast phase lasted for 58.38 seconds (93.13 seconds of total flight time) and had a final altitude of 185 km (115 mi) with a final Mach number of 26.74, which is orbital velocity and altitude. The propellant mass fractions of the air-breathing phase and rocket phase were 0.45 and 0.47, respectively, for a total vehicle propellant mass fraction of 0.71. The red vertical lines in Figures 4 and 5 mark the end of the air-breathing phase at 24.29 seconds and the blue vertical lines mark the end of the rocket phase at 34.74 seconds.

Figure 2 shows a plot of the altitude vs. time of flight throughout the entire simulation. Initially in the air-breathing phase, altitude was not gained very quickly. This was due to the vehicle's thrust fighting against the drag wall, low in Earth's atmosphere. However, after approximately 15 seconds, altitude began to increase much more rapidly. This was the approximate time at which the thrust, significantly fueled by the ramjet air compression and chemical augmentation, began to overcome the drag, and the transonic flight regime that steals kinetic energy due to excessive drag was exceeded and supersonic air compression became the dominant factor. When the vehicle switched over to rocket-propelled flight, the rate of change of altitude was approximately constant due to limited drag being reduced even further as altitude increased while incident laser power on the vehicle was being reduced due to atmospheric effects at increased ranges from the laser. Finally, the coast phase was when the linear increase in altitude began to bend over on its way to the final altitude due to a reduction in the flight-path angle, approaching the horizontal, in concert with a velocity that is being slightly reduced.

This course of events is easy to visualize using Figure 3, a plot of Mach number vs. time of flight. During the air-breathing phase, the vehicle initially accelerated very quickly to a Mach number in the transonic region, but remained there for approximately 15 seconds because the drag wall couldn't be overcome until higher altitudes were reached and the ambient air density decreased. After this time, the Mach number increased very dramatically to the final Mach number for the phase of 11.14, although a slight decline in the rate of change in velocity can be seen towards the end of the phase. This was due to air density that was reduced to such exceptionally low levels at an altitude of nearly 30 km that air compression at $M \approx 10$ was not enough to keep thrust high. The rocket-propelled flight had the most significant increase in velocity up to a Mach number of 26.5. The increase was nearly constant due to a thrust level that stayed fairly constant around 1,300 N. Finally, the coast phase showed a Mach number that initially increased to maximum of nearly $M = 27$ due to a small reduction in velocity coupled with a large increase in altitude that reduced the ambient temperature and, thus, the speed of sound. However, it then began a very gradual decrease to its final value of M = 26.74 as vehicle velocity decreased.

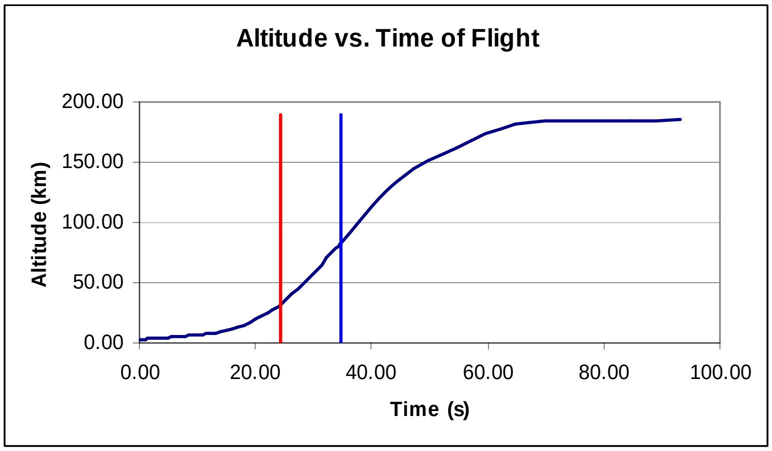

FIGURE 2. Altitude vs. Time of Flight for 10 MW Simulation

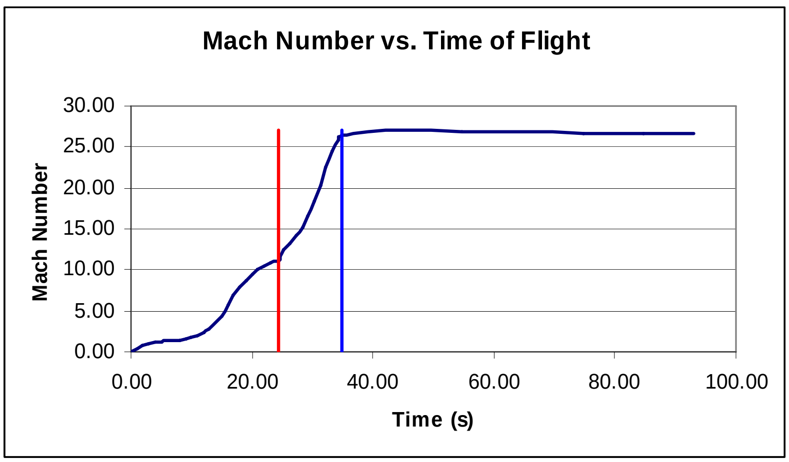

FIGURE 3. Mach Number vs. Time of Flight for 10 MW Simulation

Figure 4 is a plot of the vehicle mass vs. the time of flight. During the air-breathing phase, the mass initially decreased very gradually from 6.8 kg for the first ~15 seconds. This is due to limited or non-existent air compression in the vehicle keeping the air-breathing thrust low; therefore the chemical augmentation didn't use as much propellant as later in the flight. After the air compression became the dominant factor in the thrust, the chemical augmentation system had to increase mass flow to maintain the thrust multiplier of five. This led to a more dramatic decrease in vehicle mass. It can again be seen that, towards the end of the phase, the mass flow rate decreased due to decreased air-breathing thrust at altitudes of ~30 km. The final mass of the air-breathing phase was 3.71 kg. The mass flow rate during the rocket phase of the flight stayed relatively constant for reasons stated above, with vehicle mass terminating at 1.98 kg for vehicle structural mass and payload.

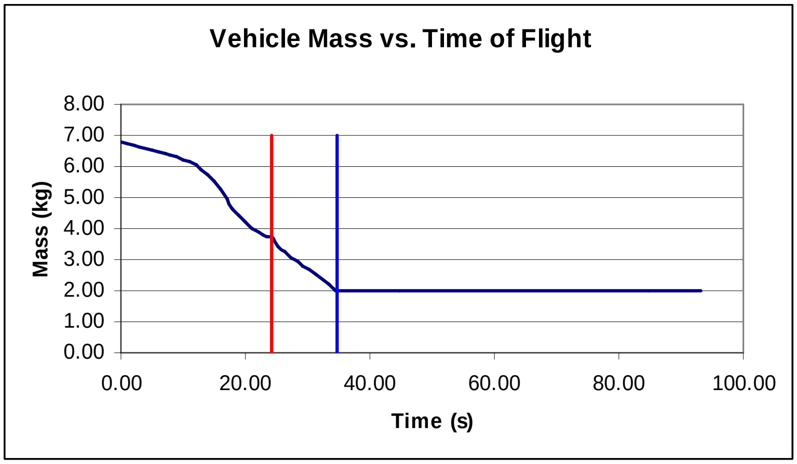

FIGURE 4. Vehicle Mass vs. Time of Flight for 10 MW Simulation

Sounding Rocket Simulations

In all sounding rocket cases (See Figs. 5 & 6), the propellant combination yielded the same performance: coupling coefficient of 3,150 N/MW and specific impulse of 300 seconds. The mass fraction of the propellant also remained the same at 0.67 while the initial mass of the vehicle remained unchanged at 630 grams. The only thing that changed throughout the four simulations was the incident laser power, ranging from a low value of 8.2 kW to a high value of 82 kW. This meant that, as laser power increased, the amount of thrust increased substantially without a corresponding increase in either total propellant mass or specific impulse. The same amount of propellant didn't last nearly as long as the laser power was increased and this resulted in much lower burn-out altitudes. In the extreme cases of 10 kW and 100 kW, the differences were monumental. The 10 kW simulation yielded a burn-out altitude of nearly 17 km after nearly 50 seconds of flight time while the 100 kW simulation lasted only 5 seconds and reached only 4.3 km altitude.

Another important point to note is in the comparison between the 10 kW and 30 kW simulations. If the 30 kW simulation is compared with the 50 kW or 100 kW simulation, the 30 kW simulation yielded the lower burn-out Mach number. However, the 10 kW simulation yielded a higher burn-out Mach number than the 30 kW simulation and a comparable Mach number to the 50 kW simulation. The most likely explanation for this is that the extremely low thrust 10 kW simulation produced very low velocities through the lower part (≤ 8 km) of the atmosphere and therefore experienced much lower drag and less kinetic energy loss than the other simulations. Its increased flight time allowed it to extend to a higher altitude than the other simulations and the ambient air density began to drop, reducing drag and allowing higher flight velocities for the same amount of thrust.

If one wishes to reach maximum velocity at a maximum altitude, it seems likely to the author that either a relatively low laser power should be used or that a high-power laser should be used, but with significant increases in vehicle mass and propellant mass fraction. For optimum velocity and altitude, as the power of the laser is increased, so should the size and mass of the vehicle and its propellant.

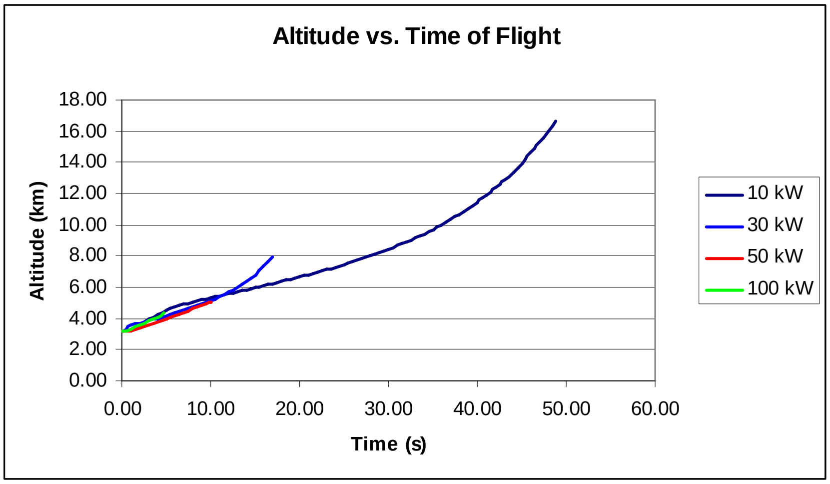

FIGURE 5. Altitude vs. Time of Flight for Sounding Rocket Simulations

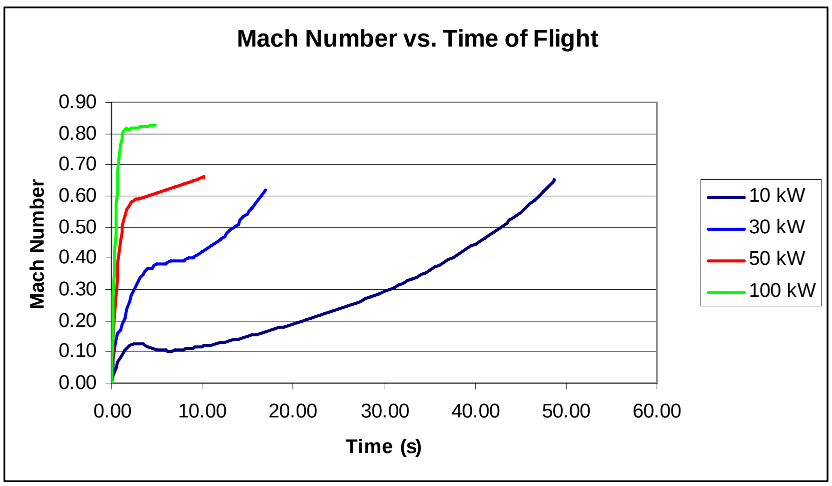

FIGURE 6. Mach Number vs. Time of Flight for Sounding Rocket Simulations

High Thrust vs. Low Thrust Parametric Study

This parametric study concentrated on the relative merits of high thrust vs. low thrust rocket flight for the LR. The vehicle was started, after an initial air-breathing phase, at an altitude of 36.8 km, a Mach number of 10, a mass of 2.27 kg (5 lbs) and the laser employed was a 1 MW 10.6 μ CO_2 laser with an initial vehicle power capture of 82%. The high thrust propellant used had a coupling coefficient of 1,000 N/MW with specific impulse of 300 seconds, while the low thrust propellant had a coupling coefficient of 385.77 N/MW and an I_{sp} of 350 seconds. The propellant mass fraction in both cases was 0.8 and all vehicle characteristics were held constant in the two simulations.

The high-thrust vehicle flight lasted for 13.02 seconds with a burn-out altitude of 79.43 km (49.4 mi) and a final flight Mach number of 22.47. The low-thrust vehicle flight lasted for 19.26 seconds with a burn-out altitude of 103.54 km (64.4 mi) and a final flight Mach number of 25.98, which is nearly orbital speed. The difference in flight time was expected due to the lower thrust and higher I_{sp} of the low-thrust flight.

Figure 7 shows a plot of altitude vs. the vehicles' time of flight for both simulations. For the first 6.5 seconds the curves lined up nearly on top of one another, signifying that the high-thrust levels were not enough to overcome atmospheric drag losses up to 55 km altitude. After this time, however, the curves began to diverge to a certain degree. It is possible that, given more propellant, the level of divergence would be far more significant than what is shown in Figure 7. It was apparent that the low-thrust vehicle didn't need additional propellant, the increased flight time coupled with comparable flight velocities, as seen in Figure 8, allowed the low-thrust vehicle to climb to significantly higher altitude, nearly 30 km higher, than the high-thrust vehicle.

According to Figure 8, a comparative plot of Mach number vs. flight time for the two vehicles, the Mach numbers of the two simulated vehicles showed very little divergence throughout the flight, which was indicative of greater kinetic energy losses in the atmosphere for the high-thrust vehicle. As in Figure 7, it appeared that in the final few seconds of the high-thrust vehicle's flight the Mach number began to increase more dramatically. Given more propellant, it is likely that the divergence would continue more markedly and a much higher final Mach number could be reached. The additional flight time of the low-thrust vehicle allowed it to reach a much higher final Mach number with significantly less kinetic energy loss through the atmosphere.

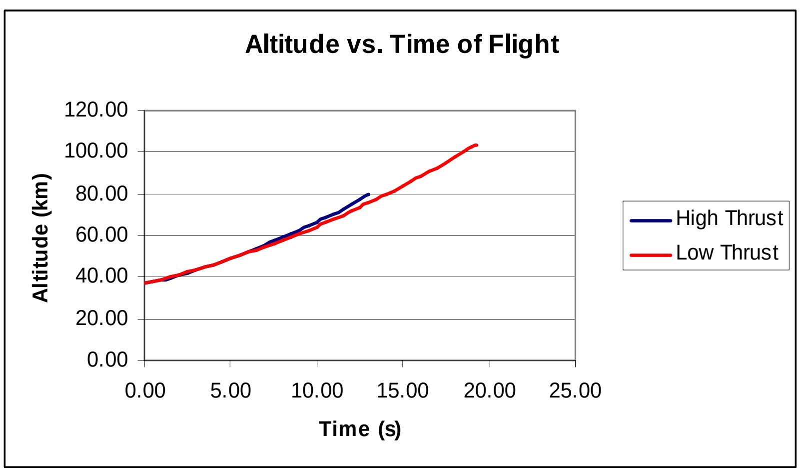

FIGURE 7. Altitude vs. Time of Flight Comparison between High-Thrust and Low-Thrust Flight

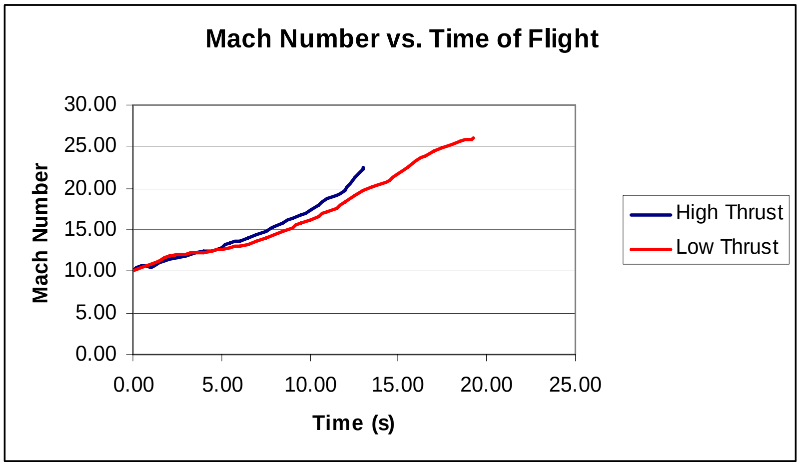

FIGURE 8. Mach Number vs. Time of Flight Comparison between High-Thrust and Low-Thrust Flight

The conclusions that can be drawn from this parametric study are that for such low initial mass applications as the LR, low-thrust propellant combinations perform better than high-thrust combinations or that a low-thrust propellant should be used initially followed by a high-thrust propellant when enough altitude has been gained. These simulations have shown that low-thrust propellants can provide much greater burn-out velocities and altitudes than high-thrust propellants without too significant an increase in laser time. High-thrust propellants may be a better choice if the user is willing to increase initial vehicle mass or increase the propellant mass fraction.

Qualitative Analysis of Vehicle Diameter during Air-Breathing Flight

Due to time constraints, a qualitative study was conducted regarding the effects on performance of altering the diameter of the flight vehicle. Starting with Equation 1 for the coupling coefficient and recognizing that A_{LR} has a R^2 dependency, the thrust of the vehicle was found to be proportional to $R^{11/4}$.

The performance of the vehicle can be defined using the thrust-to-opposing force ratio, T/(D + W), where W is the opposing force due to gravity and D is the drag force, which directly opposes the direction of motion. If it is assumed that the drag was significantly greater than the weight of the vehicle, D >> W, the expression in Equation 20 was the result, while Equation 21 shows the R^2 dependency of drag. In Equation 21, ρ is the ambient air density, V is the vehicle flight velocity, S is the profile or "wetted" area of the vehicle, which is R^2 dependent, and C_D is the global drag coefficient of the vehicle.

$$T/(D + W) \approx T/D \qquad (5)$$
$$D = \tfrac{1}{2} \rho V^2 S C_D \qquad (6)$$

Combining Equations 20 and 21 and focusing solely on the dependency of vehicle size, Equation 22 resulted. According to Equation 22, the overall performance of the vehicle increased with $R^{3/4}$ provided that the physics behind the air detonation does not change with vehicle focal diameter.

$$T/D \alpha R^{11/4}/R^2 = R^{3/4} \tag{7}$$

CONCLUSIONS

In terms of the sounding rocket simulations, given the low initial mass of the vehicles simulated, the greatest performance, in terms of altitude, will be found with lower laser powers which lead to lower values of thrust. This is only if the vehicle parameters (i.e. geometry, propellant characteristics, mass fraction, etc.) don't change through the range of laser powers considered. If one wants to see similar or greater performance from higher power lasers, it will be necessary to either increase the initial mass of the vehicle along with the propellant mass fraction or to decrease the thrust and increase the specific impulse of the propellant that is being used. Otherwise, increasing laser power will only serve to decrease the burn time by using up the propellant more quickly, this may lead to higher velocities, but at much lower altitudes. Using high-thrust, low in the Earth's atmosphere, results in an unseemly amount of kinetic energy from the propellant being negated by the effects of drag that result from high vehicle velocities. Gradual acceleration through the lower portion of Earth's atmosphere is the key to great performance.

For the MW-class LR launches to LEO, the two major phases that need to be considered are the air-breathing phase and the rocket phase. The biggest obstacle to a successful LR flight to orbit is the low-altitude, high-density portion of Earth's atmosphere from zero to ~30 km altitude. It results in the kinetic energy of propellant being wasted by major drag issues. One needs to determine a method to overcome this. The most obvious explanation would be to start the flight above 100,000 ft using something such as a balloon lift or a drop from a high-altitude aircraft. However, these methods would likely introduce major costs into a launch program.

A much more efficient idea would be to implement an air-breathing propulsion scheme for the lower portion of the atmosphere. The problem here is that the physics behind the air-detonation ramjet propulsion system precludes overcoming the drag wall low in the atmosphere. Thus, high velocities are impossible, as are significant altitudes. Two potential solutions to this that could be developed in concert with one another are chemically augmenting the propulsion system of the LR and diverting a portion of the laser energy to a point in front the LR's fore-body to break the ambient air down into plasma which has significant drag reduction and aero-heating reduction capabilities.

Another significant possibility would be to increase the diameter of the LR. Qualitative analysis shows that the performance of the LR increases as $R^{3/4}$. However, this would be a negative issue for the rocket phase of the flight as a larger diameter would result in a larger amount of drag by a factor of R^2. Given the correct propellant combination, though, and starting the rocket phase at a high enough altitude, it is likely that the increase in diameter would have only a negligible effect on the performance of the vehicle.

Simulations were conducted that compared the merits of high-thrust and low-thrust rocket propulsion during a launch to LEO. Two potential solutions were determined: low-thrust propulsion should be used for the rocket portion of LR flights due to lower kinetic energy losses up to a significant altitude; or the rocket phase should be two-phase in that the vehicle initially uses low-thrust propulsion until a certain altitude (~60 km) is reached, then high-thrust propulsion should be used to reach orbital altitude.

The full-scale launches to LEO that were conducted for a 25 cm focal diameter LR with a 10 MW, 10.6 μm, CO_2 laser were shown to be effective at bringing the LR to orbital altitude and velocity under certain conditions. The initial vehicle mass was 6.8 kg with a total propellant mass fraction of 0.71. The air-breathing phase was chemically augmented to increase thrust by a factor of five while plasma-based drag reduction techniques were used that reduced drag by 45%. The air-breathing phase had a propellant mass fraction of 0.45 for a final phase mass of 3.71 kg. The final Mach number was 11.14 and the final altitude was ~31 km. The rocket phase used Delrin® propellant with an I_{sp} = 800 seconds and a coupling coefficient of 168.77 N/MW. The propellant mass fraction of the phase was 0.47 resulting in a final phase mass of 1.98 kg. The final Mach number of the phase was 26.5 and the final altitude was ~88 km. The LR eventually coasted to its final altitude of 185 km at a Mach number of 26.74.

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